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Analysis of Electrical Interconnection Strategies in Vertical Solar Brick Walls under Partial Shading Conditions for BIPV Applications

Juan Isaza-Alvarez[1]*, Gabriela Zabala-Barrios[2], Gabriel Espitia-Mesa[3], Gilberto Osorio-Gómez[4], Jose Marulanda-Bernal[5]
[1,2,3,4,5]School of Applied Sciences and Engineering, EAFIT University, Medellín – Colombia
[1]jisazaa3@eafit.edu.co, [2]mgzabalab@eafit.edu.co, [3]gespitia@eafit.edu.co, [4]gosoriog@eafit.edu.co,
[5]jmarulan@eafit.edu.co

Abstract: *The incorporation of solar bricks into vertical wall structures presents a practical approach for the architectural integration of photovoltaic systems within Building Integrated Photovoltaic (BIPV) applications. Nonetheless, the presence of shading, whether originating from adjacent structures, self-shading phenomena, or dynamic elements, can substantially diminish both energy production and the stability of the system. This research conducts a simulation-based evaluation of diverse interconnection schemes for a vertical solar brick wall, aiming to elucidate the electrical implications of partial shading on these products. A comprehensive model of a modular photovoltaic unit at the brick scale was developed and configured into a system including sixteen interconnected bricks. Within a simulation environment, various interconnection topologies were executed, and representative shading patterns were applied for morning, noon, and afternoon conditions. Essential performance indicators, including current uniformity across connections, power output, and mismatch losses, were assessed under distinct shading scenarios. The findings indicate that diverse interconnection configurations show proper responses to partial shading, with those allowing a fairer distribution of current proving superior stability and reduced susceptibility to electrical losses among solar bricks. Moreover, control strategies based on real-time voltage and current monitoring at the brick level were seen to ease recovery after partial shadow exposure. These results inform the interconnection designs for vertical solar brick facades, thereby enabling the advancement of high-performance and dependable building integrated photovoltaic systems.*

Keywords: *BIPV, Interconnection strategies, Missmatch losses, Solar bricks, Partial shading.*

I. INTRODUCTION

The increasing concern regarding climate change and the imperative to mitigate energy consumption from non-renewable sources have accelerated the advancement of sustainable technologies across diverse sectors, including construction. Among the most promising strategies within this domain is the integration of photovoltaic systems into the building envelope, referred to as Building Integrated Photovoltaics (BIPV). This approach has gained significant relevance in recent years as part of initiatives to enhance energy efficiency and diminish the carbon footprint of buildings. In contrast to traditional photovoltaic installations, which are generally positioned on rooftops or adjacent open land, BIPV systems are embedded within the architectural framework of buildings, seamlessly integrated into components such as facades, windows, roofs, or even building materials like tiles or bricks. Within this context, the evolution and implementation of BIPV technology present numerous advantages, including optimal spatial utilization, on-site energy generation, and the incorporation of innovative materials that satisfy both aesthetic and functional requirements among diverse environmental conditions.

This study introduces an innovative approach to the incorporation of solar panels into wall designs via a component termed the “solar brick.” Each unit, similar in appearance to traditional construction bricks, integrates a small photovoltaic panel enclosed within a durable plastic cover on its frontal surface. These bricks are engineered for side-by-side installation, forming vertical walls that fulfill structural functions while concurrently generating electricity. Within this setup, each brick operates as an individual generation unit, thereby contributing to the building's electrical system. Furthermore, by generating electricity at the point of use, the system mitigates losses related to energy transmission across the electrical grid. Consequently, BIPV fosters not only the energy self-reliance of structures but also presents a practical and environmentally sustainable solution for urban settings. Nonetheless, this methodology encounters considerable challenges, particularly those concerning the vertical orientation of solar bricks and their uneven exposure to sunlight. In contrast to traditional systems installed on flat roofs with optimized tilt angles, vertical facades encounter varying solar incidence angles throughout the day and across seasons. Additionally, urban areas frequently present physical obstructions such as balconies, eaves, trees, or adjacent buildings that create partial shadows on the wall surface. These shadows impact the bricks unevenly, resulting in a non-uniform irradiance distribution and giving rise to a phenomenon known as electrical mismatch.

The academic literature indicates that mismatch losses assume critical importance when photovoltaic (PV) modules are subjected to markedly heterogeneous irradiance conditions. Even within conventional configurations, partial shading affecting a single section can substantially reduce the current output of an entire panel or series-connected string. This problem is exacerbated in facade-integrated BIPV systems, where architectural elements affect irradiance patterns and facilitate shadow accumulation over the course of the day. As a result, recent scholarly research has concentrated on the development of interconnection strategies to enhance shading tolerance, alongside the implementation of maximum power point tracking (MPPT) algorithms at the submodule or microinverter level to alleviate the consequent impact on power electronics.

In this context, the current study undertakes a comparative analysis of diverse electrical interconnection schemes utilized among multiple solar bricks installed on a vertical wall. A comprehensive brick-level model has been developed, which includes the I-V characteristics of the integrated photovoltaic panel, the mechanical properties of the unit and its plastic enclosure, in addition to real-world irradiance conditions and solar incidence angles. This model is replicated to construct an array of eight solar bricks, interconnected using various topologies, such as series, parallel, hybrid configurations, and others incorporating bypass diodes and power optimizers. To evaluate shading effects, representative scenarios are simulated for various times of the day, morning, noon, and evening; considering how shadows cast by architectural features or surrounding elements selectively influence specific bricks within the array. This methodology facilitates the evaluation of actual performance degradation due to partial shading under realistic operating conditions.

The simulations yield a comprehensive analysis of critical parameters determining the performance and dependability of the solar brick system integrated into the facade. A principal parameter examined is the electrical power output, which is directly contingent upon the incident solar irradiance on each brick and the particular interconnection topology employed. Another crucial consideration is the uniformity of current distribution across the array, specifically how electrical current flows through the interconnected bricks. Achieving homogeneous distribution is advantageous, as it diminishes the potential for hot spots and efficiency reductions caused by electrical mismatches. Significant attention is devoted to the effects of partial shading, deriving both from external sources, such as proximate buildings, vegetation, or architectural elements of the same structure, and from self-shadowing due to the vertical arrangement of the bricks. These shading effects can generate non-uniform performance among the bricks, leading to mismatch losses. To confront these challenges, advanced control strategies are enacted and scrutinized. These strategies incorporate real-time monitoring of essential electrical variables, including voltage and current at the individual brick level. Such data empowers the system to identify shading or anomalous conduct in specific bricks and adaptively adjust its operation to alleviate associated losses. As an illustration, the system may redistribute loads, initiate bypass pathways, or modify the operating points of selected modules to maintain overall efficiency.

In conclusion, the system demonstrates the capability to attain a more equilibrated distribution of current and improved power stability, even in scenarios of partial shading. This not only enhances overall energy efficiency but also prolongs the system's lifespan and diminishes the necessity for corrective maintenance. These findings advance the development of BIPV technologies that meet both aesthetic and architectural demands while providing significant levels of performance, reliability, and versatility in responding to the intricate challenges associated with urban environments.

Following this contextual framework, the text moves from a critical synthesis of the literature to the development of a numerical model that captures the electrical behavior of photovoltaic walls built with solar bricks. Section II surveys the main advances in interconnection topologies and shading-loss mitigation strategies. Section III then details the MATLAB/Simscape simulation environment, the irradiance scenarios configured, and the electrical parameters adopted. Section IV reports the results obtained for each topology under the different shading patterns, whereas Section V delves into their interpretation and highlights the design implications for modular BIPV applications. The closing insights and prospective research directions are compiled in Section VI.

II. RELATED WORK

Research on mismatch loss mitigation through interconnection topology was significantly advanced when Silvestre et al. compared Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Linked (BL), and Honeycomb (HC) configurations in a 6 × 6 array. Their results showed that TCT could recover 18% to 27% more power than SP, while also smoothing the multiple peaks typically observed in the I–V curve [1]. Subsequently, Belhachat and Larbes investigated the severity of mismatch effects and elucidated that the relative advantage of TCT is enhanced under conditions of significant shading; conversely, SP persists as a viable alternative under conditions of mild and uniform shading [2]. Prior experimental investigations, including that by Özkaya, exposed the significant susceptibility of series-connected strings. A singular shaded module can alter the maximum power point of the entire series, thereby necessitating the implementation of cross-link strategies inherent in BL and HC topologies [3]. A subsequent investigation conducted by Chowdhury et al. on diagonal shading conditions demonstrated that the HC and BL configurations have the potential to yield up to 37% greater energy output compared to the SP configuration, while also decreasing hot-spot temperatures by approximately 6 °C [4].

Static analyses have gradually evolved into dynamic studies that simulate real world conditions such as cloud movement. Recent research published in EPJ Photovoltaics demonstrated that the TCT configuration maintains the highest daily energy yield, although it incurs a resistive penalty of approximately 2.7% due to its increased number of interconnections [5]. Incorporating diurnal shading patterns, encompassing morning, noon, and afternoon intervals, previous research indicates that the BL configuration maintains string current variations within a range of ±4% over the course of the day. In contrast, the SP configuration is subject to imbalances surpassing 40% at sunset [6]. To diminish the wiring complexity inherent in TCT while maintaining energy efficiency, the Selective Cross-Tied (SCT) configuration was developed. Within this framework, Pandian and colleagues systematically incorporated cross-ties at strategically chosen nodes, resulting in power increases of up to 209% in comparison to SP within 4 × 4 arrays exposed to diagonal shading [7]. In a subsequent study, Khan et al. introduced a cross-diagonal configuration that reallocates interconnections in accordance with predicted irradiance profiles, which resulted in reported energy gains of 9–12% and a decrease in thermal dispersion [8]. Concurrently, El Iyssaouy developed novel configurations influenced by logic-based puzzles: the "Sudoku" pattern exhibited an 8% improvement on average over traditional topologies under conditions of random shading [9], whereas the variations "Calcudoku" and Odd Even exhibited significantly enhanced power gains and optimization in power-to-wiring-length ratios [10].

Current advancements have furthered the scope of electrical modeling and the evaluation of performance metrics. Picault devised a daily forecasting methodology that integrates shading dispersion coefficients and MPPT efficiency to appraise the energy output of diverse interconnection topologies [11] more accurately. Expanding upon this foundational basis, Kareem presented the Modified Series-Parallel (MSP) metric, illustrating that although the Total Cross-Tie (TCT) is more effective in scenarios with uneven vertical shading, the MSP displays enhanced performance in situations characterized by horizontal or irregular shadowing patterns [12]. Comprehensive performance metrics, including current uniformity, equivalent resistance, and relative power loss, have facilitated the evaluation of not only immediate energy output but also thermal reliability and anticipated system longevity [13]. Concurrently, the shift from the basic "generator + diode" model to more sophisticated two-diode representations, which incorporate both series and parallel resistive components, has augmented the modeling of rapid irradiance transients and refined mismatch loss calculations [14].

Despite these advancements, three significant limitations persist: (i) most studies are restricted to arrays of conventional PV modules with dimensions $\geq 3 \times 3$, neglecting the potential of small-area modules such as solar bricks (≤ 0.1 m^2); (ii) almost all simulations concentrate on horizontal shading scenarios typical of coplanar rooftop systems, thereby ignoring the vertical shading patterns inherent in BIPV facades; and (iii) reconfiguration strategies predominantly rely on global irradiance measurements, without integrating module-level voltage and current data crucial for executing adaptive switching mechanisms.

The current study seeks to address these shortcomings by incorporating insights from SP, TCT, BL, and HC interconnection topologies into a vertical system comprising eight solar bricks. It applies to representative shading conditions for morning, noon, and afternoon periods while integrating local electrical sensing on each brick to examine distributed switching strategies. In doing so, this research addresses the scales, orientations, and control challenges identified in literature, offering practical guidelines for designing high-performance photovoltaic facades that can sustain operational stability under dynamic shading conditions prevalent in dense urban environments.

III. APROACH

The electrical interconnection topology of a photovoltaic (PV) array is pivotal in determining the extent of energy conservation or loss under conditions of partial shading. This research undertakes a comparative analysis of four configurations frequently cited in academic literature: Series-Parallel (SP), Total-Cross-Tied (TCT), Honeycomb (HC), and Bridge-Linked (BL). Although all these configurations are founded on the fundamental principle of current dispersion to prevent a single branch limitation from adversely affecting the overall array performance, they exhibit substantial differences in terms of cross-connections, total conductor length, and structural complexity. The subsequent section elucidates the operational principles of each topology and articulates the justification for their inclusion within the simulation framework.

A. Series-Parallel (SP)

The Series-Parallel (SP) configuration connects Ns cells in series to increase the voltage, subsequently connecting Np of these series-connected strings in parallel to improve the current, as can be seen in Figure 1. Owing to its straightforward design, this configuration remains the prevailing reference topology within both industrial and academic domains. Nonetheless, under conditions of partial shading, the current across the entire array is limited by the branch receiving the least irradiation, causing significant power losses up to 70% when merely 25% of the surface area is subjected to diminished irradiance [15]. Empirical research has also documented the development of hot spots in the most illuminated modules, with observed temperature elevations of 5–8 °C above the array mean [16].

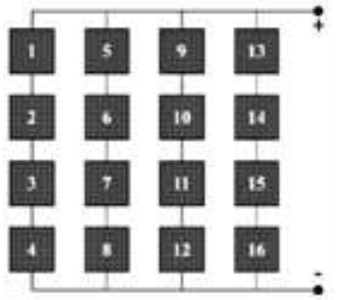

Figure 1 Series- Parallel configuration (SP)

B. Total-Cross-Tied (TCT)

The Total-Cross-Tied (TCT) configuration (Figure 2) preserves the fundamental Series-Parallel arrangement while incorporating supplementary horizontal interconnections that connect nodes situated at the same row level across neighboring strings. This mesh-like structure facilitates current redistribution among branches, thereby substantially enhancing the array's resilience to partial shading by permitting excess current from less shaded strings to circumvent those with diminished irradiance.

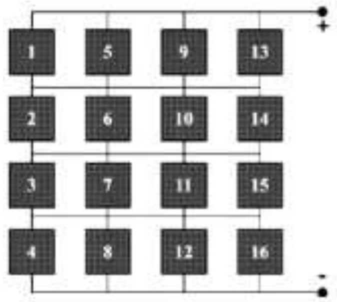

Figure 2 Total-Cross-Tied configuration (TCT)

C. Honeycomb (HC)

As can be seen in Figure 3, the Honeycomb (HC) topology restructures the interconnections to establish interleaved hexagonal cells, forming a configuration that both visually and functionally mirrors a honeycomb. Within this configuration, critical nodes are allocated across multiple closed meshes, allowing the current to navigate through alternative diagonal and lateral pathways if primary conduction routes are obstructed. This architecture enhances fault tolerance and mitigates mismatch losses under intricate shading conditions.

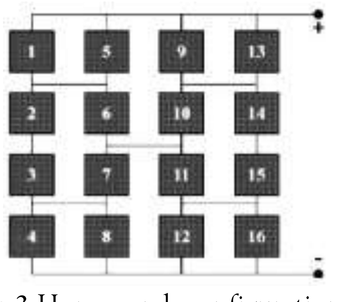

Figure 3 Honeycomb configuration (HC)

D. Bridge-Linked (BL)

The Bridge-Linked (BL) configuration incorporates conductive bridges between strategically selected nodes within the PV array, as can be seen in Figure 4. These supplementary connections facilitate the rerouting of current flow when individual cells or entire rows experience shading, thus augmenting the system's continuity and resilience. BL serves as an intermediary solution between the simplicity of SP and the complexity of TCT configurations, presenting a beneficial compromise between efficiency and wiring demands across diverse operating conditions.

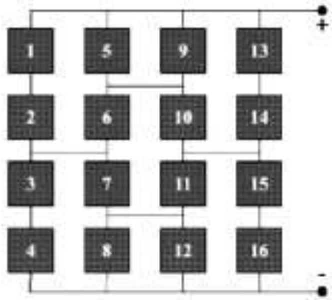

Figure 4 Bridge-Linked configuration (BL)

Collectively, these four configurations encompass a comprehensive range of interconnection strategies: from the industrial standard (SP) to the approach that maximizes current dispersion (TCT), along with intermediate solutions that harmonize wiring complexity and performance benefits (HC and BL). Their divergent behaviors under different shading conditions render them an ideal testbed for evaluating modular PV walls, where shadows shift throughout the day and differ between rows of solar "bricks." The following section elucidates the simulation methodology utilized to quantify string currents, I–V operating points, and mismatch losses within a vertically oriented array.

E. Simulation

The numerical model was comprehensively implemented in MATLAB through the utilization of the Simscape Electrical / Specialized Power Systems library. Each photovoltaic brick, represented as a 10 W commercial mini-module delineated by the single-diode model with an open-circuit voltage Voc=7.2V and a short-circuit current Isc=1.8A, was configured to receive separate irradiance and temperature inputs via the Solar Cell blocks. A total of sixteen units were arranged in a 4 × 4 matrix, encompassing four columns and four rows, to accurately simulate the modular layout typically adopted in BIPV facades based on solar bricks. The electrical topology of the array was parameterized utilizing an adjacency matrix A. A specialized script was devised to automatically generate the corresponding Simscape code for each interconnection scheme (Series-Parallel, Total-Cross-Tied, Bridge-Linked, and Honeycomb), as well as to calculate the additional linear resistance introduced by each topology: 28 mΩ in TCT, 14 mΩ in BL, and 34 mΩ in HC.

The experimental campaign was systematically organized around four shading scenarios, adapted from comparative analyses of 4 × 4 photovoltaic arrays and specifically tailored to a vertical facade context. Figure 5 illustrates the eight irradiance levels employed in the simulations, ranging from 300 to 1000 W/m², which are encoded using a grayscale color map. This identical gradient was utilized to allocate irradiance values to each brick within the case diagrams.

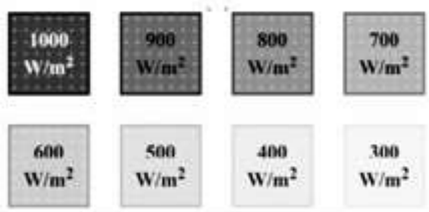

Figure 5 Scale of settings

In Case 1 (Figure 6), the four modules located in the first column (modules 1, 5, 9, and 13) function at an intermediate irradiance of 600 W/m², whereas the remaining twelve modules receive full sunlight at 1000 W/m², simulating the horizontal shadow cast by an architectural overhang.

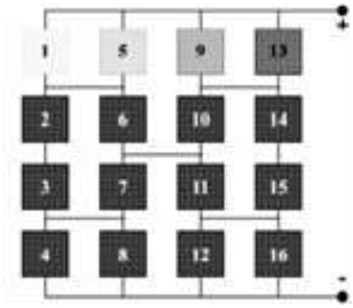

Figure 6 Case 1

Case 2 (Figure 7) emulates the impact of a lateral obstruction, such as a side wall: modules in the first row (modules 1–4) are subjected to a vertical irradiance gradient of 600, 500, 400, and 300 W/m², respectively, while the remaining modules are fully illuminated.

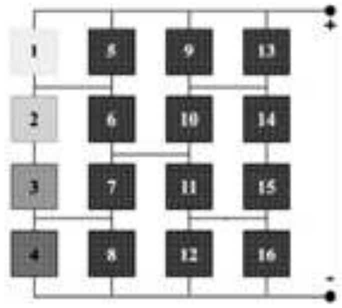

Figure 7 Case 2

Case 3 (Figure 8) imitates asymmetric morning shading. Modules 1 and 13 operate at 500 and 700 W/m², respectively, while modules 4 and 16 decrease to 300 W/m². This configuration forms an 'L'-shaped shading pattern impacting both the upper and lower branches of the array simultaneously.

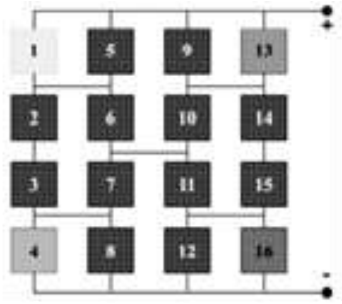

Figure 8 Case 3

Case 4 (Figure 9) exemplifies diagonal shading induced by proximate obstructions. Modules 6, 11, and 16 operate at 600, 400, and 300 W/m², respectively; the modules situated along the main diagonal are set at 900 W/m², with all others exposed to full irradiance.

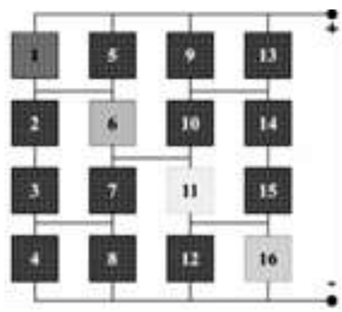

Figure 9 Case 4

IV.RESULTS

To compare the efficacy of various solar cell interconnection strategies under conditions of partial shading, numerical simulations were performed on a 4 × 4 array of photovoltaic bricks exposed to five distinct irradiance scenarios: one involving uniform illumination (absence of shading) and four involving varying distributions of shading. The interconnection topologies that were assessed include Series-Parallel (SP), Total Cross-Tied (TCT), Honeycomb (HC), and Bridge-Linked (BL). The performance was evaluated based on the maximum power output (Pmax) and the percentage of mismatch loss (ML %), both of which were calculated relative to the uniform illumination case. In this baseline scenario, a reference power output of Pmax = 176 W was established for all configurations.

A. *Maximum power generated (Pmax)*

Table 1 illustrates the maximum power output (Pmax) achieved for each interconnection configuration across the five shading scenarios. Under partially shaded conditions, the TCT configuration consistently demonstrates the superior power output in all scenarios, with the HC configuration exhibiting closely comparable performance. For example, in Case 2, the TCT configuration achieves a Pmax of 152.94 W, whereas the HC configuration attains 150.83 W. Conversely, the SP configuration evidences the lowest efficacy under critical shading conditions, with Pmax values measured at 115.15 W in Case 1 and 115.16 W in Case 4.

Table I: Maximum Power Output (Pmax)

Shading Profile	*SP*	*TCT*	*HC*	*BL*
No shading	176.00	176.00	176.00	176.00
Case 1	115.15	118.93	117.95	117.74
Case 2	146.22	152.94	150.83	149.49
Case 3	145.37	151.45	150.66	147.70
Case 4	115.16	152.93	150.91	117.99

These findings indicate that more compact and dispersed interconnection configurations, such as TCT and HC, improve current redistribution under conditions of non-uniform irradiance. This, in turn, alleviates the adverse effects of shaded cells on the overall performance of the array.

B. *Mismatch Loss (ML %)*

Table 2 illustrates the mismatch loss percentages (ML %), defined as the ratio of the power output under shaded conditions to the ideal power output under uniform illumination. The findings suggest that TCT and HC configurations consistently demonstrate high performance across all scenarios, with average ML % values of 85.48 % and 84.81 %, respectively. Conversely, the SP configuration, which represents the conventional series-parallel approach, exhibits a significant performance decline under shading, with an average ML % of 79.26 %, and critical values as low as 65.43 % in Case 1.

Table II: Mismatch Loss Percentage (Ml %)

Shading Profile	**SP**	**TCT**	**HC**	**BL**
No shading	100.00	100.00	100.00	100.00
Case 1	65.43	67.57	67.02	66.90
Case 2	83.08	86.90	85.70	84.94
Case 3	82.37	86.05	85.60	83.92
Case 4	65.44	86.89	85.74	66.47
Average	79.26	85.48	84.81	80.85

Within the most extreme shading scenario (Case 4), the TCT configuration sustains an efficiency level of 86.89%, in contrast to the SP configuration, which attains only 65.44%, indicating a relative performance discrepancy surpassing 21%. This observation substantiates the assertion that more advanced interconnection topologies, such as TCT and HC, demonstrate markedly greater efficacy in mitigating the detrimental impacts of partial shading in modular PV systems.

V. DISCUSSION

The findings of this study underscore the significant influence that interconnection topology exerts on the energy efficiency of photovoltaic (PV) arrays when subjected to partial shading conditions. Although the quantitative results have been previously presented, it is pertinent to examine the underlying physical mechanisms responsible for the observed discrepancies, as well as the practical implications for the design of real-world systems.

An essential understanding is the significant advantage conferred by topologies with an elevated interconnection density, such as TCT and HC. Their capability to sustain high power output and efficiency under conditions of non-uniform irradiance is not incidental; it is fundamentally embedded in their electrical architecture. By facilitating multiple parallel current pathways between cells, these topologies diminish the likelihood of performance bottlenecks instigated by isolated shaded cells. Notably, TCT emerges as the most robust, distributing both voltage and current stresses more uniformly across the array. This configuration not only safeguards the system from abrupt power reductions but also enhances the output stability under varying shading scenarios. Although HC does not achieve the same level of redundancy as TCT, its hexagonal configuration still offers adequate current rerouting potential to surpass simpler schemes in performance. Furthermore, its structural design may offer a favorable compromise between performance enhancement and physical layout limitations, particularly in modular or custom-shaped BIPV installations.

The BL configuration, although less effective in certain performance metrics, nonetheless presents advantages over the traditional SP layout. This observation indicates that even modest improvements in interconnection can provide resilience benefits with minimal complexity. However, the BL configuration's limited capacity to manage diagonal or scattered shading highlights the necessity of choosing topologies based on the anticipated shading profile of the installation site. Conversely, the SP layout's inadequate performance in all shading scenarios accentuates its unsuitability for environments characterized by dynamic or localized shading. Its vulnerability is inherent in the series arrangement, where the output current of the entire string is restricted by the weakest (most shaded) cell. This phenomenon results in substantial mismatch losses, as clearly demonstrated in both simulations and empirical tests.

In addition to electrical performance, this study highlights the importance of implementation considerations. Although TCT offers superior overall performance, its higher wiring density may increase installation complexity and material expenses. Consequently, system designers must evaluate the trade-offs between efficiency improvements and practical viability. For projects with stringent space, cost, or modularity limitations, HC or even BL may provide effective alternatives delivering significant enhancements compared to traditional layouts. Furthermore, the consistency observed between simulated and experimental data underpins the reliability of the proposed modeling framework. Despite variations in scale and real-world measurement noise, the relative performance ranking of the interconnection schemes remained consistent, validating the utilization of simulation-based design in early-stage PV system planning. In summary, this analysis confirms that advanced interconnection topologies substantially reduce mismatch losses and enhance energy yield under partial shading, with TCT and HC emerging as optimal solutions. Their implementation is particularly advisable for systems anticipated to operate under irregular or transient shading conditions, such as in urban, agricultural, or architecturally integrated environments.

VI. CONCLUSIONS

Conventional Series-Parallel configurations continue to predominate in commercial module design due to their simplicity and cost-effectiveness. However, they are vulnerable to partial shading commonly observed in urban and architecturally integrated settings, rendering them a less optimal option for emerging Building-Integrated Photovoltaics (BIPV) solutions such as solar bricks.

Among the topologies examined, Total Cross-Tied (TCT) and Honeycomb (HC) configurations exhibited superior performance in mitigating mismatch losses, with TCT consistently delivering the highest energy output across both simulated and experimental scenarios. These findings are not solely theoretical but bear direct implications for the design of modular BIPV systems, where the geometry and exposure of each unit (e.g., solar bricks embedded in facades or ventilated walls) exhibit high variability and vulnerability to shading from structural elements, vegetation, or adjacent buildings.

From a critical engineering perspective, the advantage of TCT resides in its capability to dynamically redistribute current across the array, thereby minimizing the impact of localized shading and preserving system-level performance. Nevertheless, this advantage comes with the drawback of heightened wiring complexity, which may present challenges in miniaturized or prefabricated formats such as solar bricks. Conversely, HC offers a more balanced compromise by maintaining high performance with lower implementation density, which aligns more compatibly with the manufacturing constraints and spatial modularity of ceramic or composite solar bricks.

Prospectively, the integration of these interconnection strategies into next-generation BIPV products should be prioritized in design rather than considered as subsequent optimization. Future research should investigate hybrid or adaptive interconnection schemes, potentially incorporating reconfigurable electronics or bypass logic at the micro-module level to dynamically adjust to shifting irradiance patterns. Furthermore, coupling these topologies with advanced power electronics, such as module-level DC-DC optimizers or embedded MPPT algorithms, could unlock significant efficiency gains and resilience in real-world BIPV deployments.

In conclusion, this work establishes a critical foundation for re-evaluating the internal architecture of modular PV elements like solar bricks. Advancing beyond conventional wiring schemes and embracing interconnection strategies optimized for real-world shading, the photovoltaic industry can attain not only higher energy yields but also enhanced architectural flexibility, aesthetics, and functional integration, all of which are essential criteria for the widespread adoption of solar energy in the built environment.

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